Evolution of Fine-Grained Sediment Deposits over Moderate to Long Time Scales

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LONG-TERM GOAL

My long-term goal within the STRATAFORM program is to increase our understanding of the processes controlling the formation, reworking and preservation of event-scale stratigraphy on the continental shelf.

OBJECTIVES

The objectives of this project for FY99 have been to 1) begin coupling a 1-dimensional shelf sediment transport model to a model for bed consolidation; 2) investigate the controls on event bed formation and preservation on 100-year time scales; and 3) continue to apply our 2-dimensional shelf sediment transport model to the Eel shelf to understand patterns of net erosion and deposition and the evolution of bed surface texture on event time scales.

APPROACH

My approach combines model development and application with data analysis to better understand shelf sediment transport processes, facilitate data analysis, and improve our predictive capabilities. This approach yields insights into transport and bed processes at time scales of events, decades to a hundred years (~ period of record), and geological time scales (1000's years or more).

WORK COMPLETED

Model development during the past year has primarily focussed on extending the one-dimensional shelf sediment transport model to include 1) episodic net deposition; 2) flocculation of suspended sediment; and 3) bed consolidation. The first of these is complete. A simplified form of particle flocculation has been implemented, but a more complete formulation is still being developed in a time-dependent version of the transport model. The appropriate equations for bed consolidation have been developed and coded in a numerical model, but it has not yet been coupled to the sediment transport model. This work will be presented in a talk at the AGU Ocean Sciences meeting in January, 2000.

The significance of episodic deposition on event bed formation and preservation was investigated using the shelf sediment transport model in conjunction with wave, current, and flood, sediment, and biological mixing data from the Eel shelf for 100-year time scales. The results are described in a paper submitted to a special issue of Oceanography (Wiberg, submitted).

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The two-dimensional, time-dependent model developed by Courtney Harris during the last few years of this project is described in a paper (Harris and Wiberg, in press) accepted for publication in a special issue of *Computers and Geosciences* devoted to modeling continental margins. A second paper is in preparation describing the application of the model to shelves like the Eel shelf (Harris and Wiberg, in preparation).

RESULTS

Event bed formation and preservation

The thickness of event beds produced by storm resuspension on the Eel shelf increases with increasing wave conditions, but the rate of increase is limited by effects of stratification that develop when there is a large difference in shear velocity between the wave boundary layer and the current bottom boundary layer. Shear velocity in the wave boundary layer increases with wave height and/or decreasing water depth. Maximum orbital velocity at a water depth of 50 m reached 1.4 m/s during recorded wave conditions (17 years), corresponding to a shear velocity of roughly 8 cm/s. In contrast multi-year records of currents speeds 1 mab at several depths across the Eel shelf reach peak speeds of 60 cm/s (shear velocities of roughly 2.5). Because waves and currents are poorly correlated and episodes of high bottom stress on the Eel shelf are almost always associated with large waves, high bottom stress events are often characterized by large wave-current differences in shear velocity that lead to stratification-inhibited suspended sediment volumes and hence event bed thickness. If the maximum recorded wave and current conditions occurred simultaneously (very low probability event), then estimated storm bed thickness due to resuspension is only about 12 cm for an unconsolidated silty sand bed at a depth of 59 m on the Eel shelf. As this is close to average bioturbation depth (~ 10 cm), the preservation potential for even this extreme storm bed would seem low.

Preservation potential would increase in event bed thickness were augmented by net deposition due to flux convergence or flood sedimentation before bioturbation had time to rework it. STRATAFORM studies by Harris (1999) and Zhang et al. (1999) indicate that this process could produce several centimeters of net deposition at mid-shelf depths on the Eel shelf. However, the role of this process in long-term accumulation seems limited because it represents a redistribution rather than a net addition of sediment to the shelf. In contrast, river flooding has added introduced large volumes of fine-grained sediment to the Eel shelf. Based on observed flood-bed thicknesses from the 1995 and 1997 Eel River floods, it is likely that the 5 largest floods (~25% of cumulative sediment discharge to the shelf during the 85-year record) combined to produce up to about 40-cm of net deposition during the last 50 years. Both mechanisms of net deposition are closely linked to the same events that produce the storm beds in the first place.

The magnitudes and frequencies of flood deposition compared to storm-bed formation on the Eel shelf suggest that the potential for preservation of a storm bed produced by a moderate to large storm is much greater if it accompanied by or just precedes a large flood. They also suggest that storm beds preserved in the geological record of depositional margins are more likely to have formed by combined storm and flood action rather than by a storm alone. Application of the shelf sediment transport model with steady accumulation vs. episodic deposition confirms the importance of episodic sedimentation in preservation of event beds.

Bed consolidation

The evolution of bed porosity with time and depth in fine-grained sediment is linked to changes in threshold entrainment conditions for resuspension. Two approaches have been taken to describe consolidation: one developed from the perspective of soil compaction and the other developed from the perspective of settling of a dense suspension. Toorman (1996) clarifies the relationship between these two approaches and provides a unifying theory that is used as the starting point in developing a model of shelf bed consolidation. The resulting equation

$$\frac{\partial \phi}{\partial t} = \frac{\partial}{\partial z}\left[w_o \phi + \left(\frac{w_o}{\left(\rho_s - \rho_f\right) g} \frac{d\sigma'}{d\phi} + D_B \right) \frac{\partial \phi}{\partial z} \right]$$

where ϕ is bed porosity, w_o is hindered settling rate, σ' is effective stress, ρ_s is sediment density, ρ_f is fluid density, g is graviational acceleration and D_B is biodiffusion rate. This equation is similar in form to the time-dependent suspended concentration equation, and direct analogies can be drawn between terms in the two equations. If we start by assuming that biodiffusion is not a major influence on consolidation, then solving for porosity as a function of depth and time requires a relationship between porosity, ϕ, and effective stress, σ'. This closure condition must be determined empirically and will depend on characteristics of the sediment including mineralogy and organic content. Recent work by Boudreau and Bennett (in press) suggests a relationship of form for the relationship based on the field measurements of Bennett et al. (1999) from various margins, including the Eel margin (although at depths beyond the shelf break).

The equation for porosity must be solved numerically. An implicit iterative solution similar to those used to solve Richards equation for infiltration into unsaturated soils is well suited to this problem. Proper specification of the boundary conditions is more problematic. Solving the equation requires values for the porosity or porosity gradient at the top and bottom of the model domain. There are several possible approaches to setting the bottom condition that are being explored. The top condition requires that porosity at the bed surface be set. It is not clear how to set this other than by measurement. Detailed bed measurements by Drake and by Wheatcroft provide values that can be used as a starting point in setting the surface concentration. The sensitivity of the solutions to specific choices of boundary conditions is now being investigated.

Application of the two-dimensional, time-dependent shelf transport model

A primary motivation for developing the two-dimensional model was to investigate the relative importance of cross-shelf wave energy gradients, cross-shelf sediment size variations, and variations in currents across the shelf to net sediment deposition and erosion. Application of the model, which couples shelf sediment transport with bed erosion and textural modification, to wave, current, and sediment conditions typical of the Eel shelf during a storm event, demonstrates that cross-shelf gradients in wave shear stress and sediment size have significant effects on sediment redistribution on the time scale of a typical storm event. The decrease in bed shear stress with increasing water depth results in mean offshore transport even when net currents are shoreward. Because fine grains are more easily suspended and are transported farther than coarse grains, this offshore bias in transport on the shelf implies that redistribution during energetic wave events may account for the distribution of fine sediment on modern shelves.

IMPACT/APPLICATION

One clear result of applying the two-dimensional model to the Eel shelf is that moderate to large storms can winnow the fine sediment from the active layer at inner-shelf depths where the bed is a silty sand on the time scale of a single event. One expected result of the bed consolidation modeling study is that there is a time-scale associated with consolidation of a newly deposited layer of fine-grained sediment that influences the availability of that sediment for subsequent suspension owing to increases in entrainment threshold. This suggests that there are processes at work in both silt beds and silty sand beds that limit the availability of fine sediment for suspension to something less than (perhaps considerably less than) the potential for the flow to transport that sediment. While limits on availability have been recognized before, the significance for assessing long-term transport rates and bed reworking has not, nor has a physical basis been established for the limits in fine-grained beds. This work in progress should help resolve these issues. It will also permit detailed calculations of bed reworking over time, and with observed flood input, will produce profiles of bed sediment size that can be compared to Dave Drake's detailed time series of measured bed size profiles on the Eel shelf.

TRANSITIONS

Several investigators are now using our one-dimensional shelf sediment transport model. Notable, Peter Traykovski is using the model to examine the potential for stratification-limited suspension of flood sediment under high wave conditions to generate fluid-mud levels of near-bed suspended sediment concentration and comparing the results to high ABS data from the Eel shelf.

The bed consolidation modeling requires consideration of the factors controlling porosity. One of these is organic material. Organic content of bed sediments is also a primary control on partitioning of organic contaminants between sediment and pore water in the bed. Thus this study and the study I am undertaking within the Harbor Processes program are examining related factors from different perspectives that may increase our understanding of the control that bed properties has on suspension and contaminant transport.

RELATED PROJECTS

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